SIMILARITY MODELING FOR ATMOSPHERIC ACOUSTICS

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ABSTRACT

Acoustic propagation in the atmosphere depends on several environmental parameters. One of the parameters is the atmospheric profile which consists of temperature, vector wind speed, humidity, and pressure from the ground to some height in the planetary boundary layer. The problem is many times there are no atmospheric profiles available for the time, location, or season of interest. One method to obtain an atmospheric profile is to use a similarity model to generate a temperature and wind speed profile. However, the parameters to construct a similarity profile such as the friction velocity, temperature scale, virtual temperature scale, humidity scale, and Monin-Obukhov length are not easily obtained by the average user. An approach has been developed to construct similarity-based atmospheric profiles using readily available data feeding a surface energy budget model. The atmospheric profiles created using this method are valid for performing calculations of acoustic propagation over short ranges (less than 5 km). The similarity-based profiles are only valid for the surface layer, which limits the propagation range. Even with this limitation, similarity-based generated profiles allow users to perform estimates on the attenuation of sound by the environment.

1.0 INTRODUCTION

To model the propagation of sound through the atmosphere, one must know the sound speed profile. In order to calculate the sound speed profile, one must have information about the state of the atmosphere. Normally this information is in the form of the temperature and vector wind speed profiles. However, these profiles may not be available for the location or time-of-the-year desired.

Similarity theory was originally developed in the 1940's by A.N. Kolmogorov, A. S. Monin, and A. M. Obukhov in the Soviet Union (Panofsky & Dutton, 1984). This work lead to the Monin-Obukhov Similarity Theory. Basically what similarity does is to perform a dimensional analysis on an area of meteorology and numerically fit the measured data to an empirical form of the equation. What results from this technique is a reduction of data curves (spectrum, profile, etc) for different conditions to one type of curve or a family of curves based on the state of the atmosphere. Once a set of similarity equations are derived for a type of profile and using a simple set of measurements, a profile can be constructed based on the similarity equations.

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2.0 PROPAGATION THEORY

Meteorological phenomena can have a significant effect on the received sound field. The meteorological phenomena affecting the sound speed profile in are: pressure, temperature, vector wind speed, and humidity. The sound speed in air is (Pierce, 1981)

$$c(T) = \sqrt{\frac{\gamma RT}{M}}$$

where γ is the ratio of specific heats, R is the universal gas constant, and M is the molecular weight. The effective speed of a propagating sound wave equals the sound speed plus the component of the wind in the direction of propagation. The temperature, wind speed, and direction are the primary factors which influences the acoustic propagation conditions. An increasing sound speed with height causes the sound to be refracted down to the ground and is reflected resulting in long propagation distances. A decreasing sound speed with height causes the sound to be refracted up away from the ground resulting in very poor propagation conditions. (Noble, 1992) Typically, the first condition occurs at night due to a nocturnal inversion and the other condition during a bright sunny calm day.

3.0 SIMILARITY THEORY

In the surface layer, mechanical and thermal forcing are the primary driving forces. Monin and Obukhov introduced scaling parameters allowing the state-of-the-atmosphere to be described which were independent of height. The scaling parameters are the friction velocity (u_*), scaling temperature (T_*), and the scaling length (L) with a normalized height $\zeta = z/L$. The temperature and wind speed profiles are calculated using (L'Esperance et.al., 1993)

$$u(z) = \frac{u_*}{k}\left[\ln\frac{z}{z_o} - \Psi_M\left(z/L\right) + \Psi_M\left(z_o/L\right)\right]$$

and

$$T(z) = T(z_t) + \frac{T_* P_t}{k}\left[\ln\frac{z}{z_t} - \Psi_H\left(z/L\right) + \Psi_H\left(z_t/L\right)\right]$$

where k is the von Karman’s constant (0.4), z_o is the aerodynamic roughness length, z_t is an arbitrary height and P_t = 0.74. The universal functions used in this development are

$$\Psi_M(\zeta) = \Psi_H(\zeta) = \frac{3}{2}\ln\left(\frac{1-\phi^{-1}+\phi^{-2}}{3}\right) + \sqrt{3}\tan^{-1}\left(\frac{2\phi+1}{\sqrt{3}}\right), \qquad \zeta < 0$$

$$\Psi_M(\zeta) = \Psi_H(\zeta)/P_t = -4.7\zeta, \qquad \zeta > 0$$

where

$$\phi_M(\zeta) = \begin{Bmatrix} (1-15\zeta)^{-1/3} & \zeta < 0 \\ 1+4.7\zeta & \zeta > 0 \end{Bmatrix}$$

$$\phi_H(\zeta) = \begin{Bmatrix} (1-9\zeta)^{-1/3} & \zeta < 0 \\ 1+(4.7/P_t)\zeta & \zeta > 0 \end{Bmatrix}$$

The problem is what are good values for the friction velocity, scaling temperature, and scaling length for different locations, time of day, and seasons of the year. In order to determine these parameters, energy balance model developed by Rachele and Tunick (Rachele & Tunick, 1994) was employed. The energy balance model is constrained to require a minimum number of conventional meteorological inputs at a 2m-reference level. The inputs include temperature, pressure, relative humidity, and wind speed. The model also requires a judgment of soil type and moisture, cloud characteristics, day-of-the-year, time-of-day, and longitude and latitude of the site of interest. Nearly all of these inputs are measured for most areas of the world and charts are available to estimate the soil characteristics. Using these inputs, the energy balance model calculates the similarity relations required to calculate the temperature and wind speed profiles.

4.0 APPLICATION

To create a meteorological profile, a calculation is made with the energy balance model using the input information about the area of interest. For an example, lets create a profile for a windy spring day. Figure 1 shows the input information for this case. The location is the southeast coast of the U.S. The energy balance model calculates the similarity parameters based on this input. For this case, the model calculated a friction velocity of 0.874 m/s, scaling temperature of $0.0279^{o}C$, and a scaling length of -4638.1 m. These similarity parameters can now

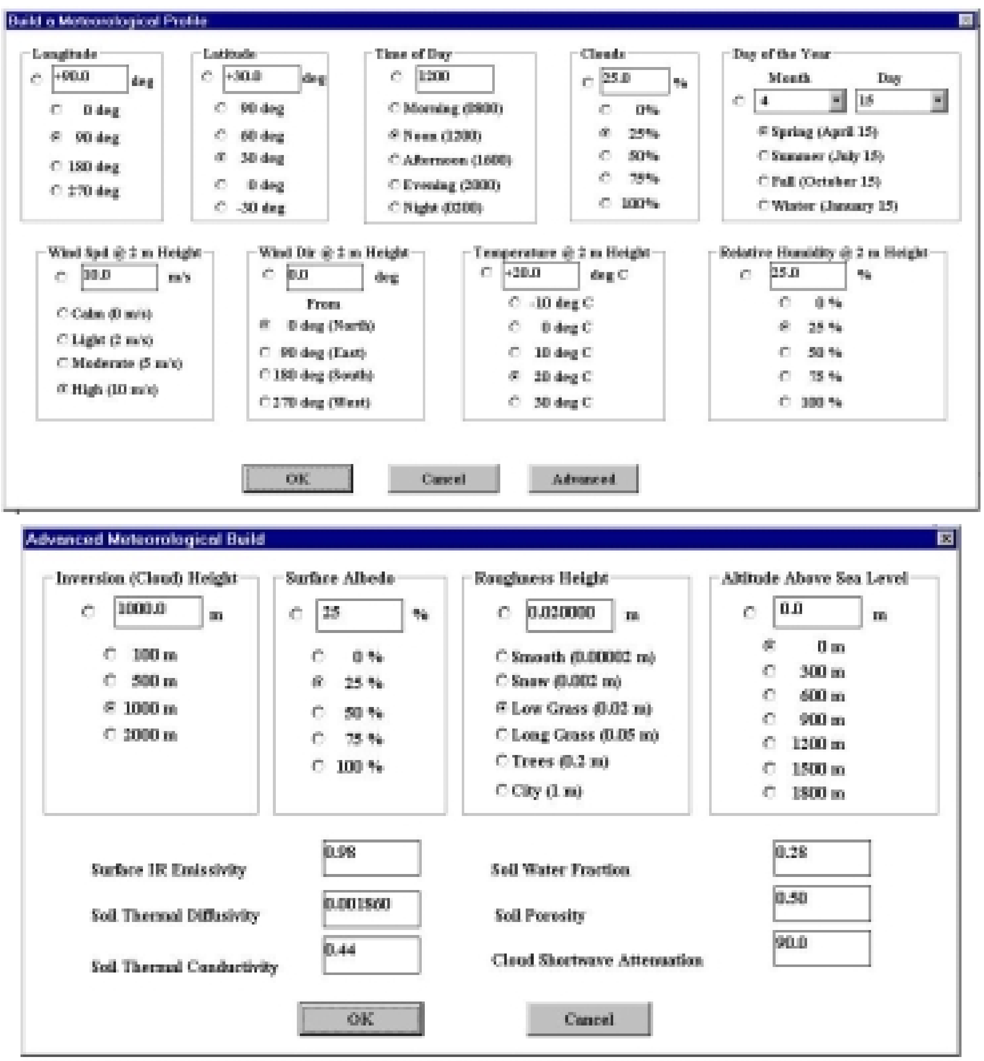

Figure 1: Input for energy balance model for a windy spring day.

be used with the similarity equations previously listed to calculate the temperate and wind speed profiles. On windy sunny days, the wind profile will dominate the sound speed profile. Figure 2 shows the sound speed profile calculated using the temperature and wind speed profile calculated from the similarity relations. Since the wind speed profile dominates the behavior of the sound speed profile, the sound speed profile is dependent on the

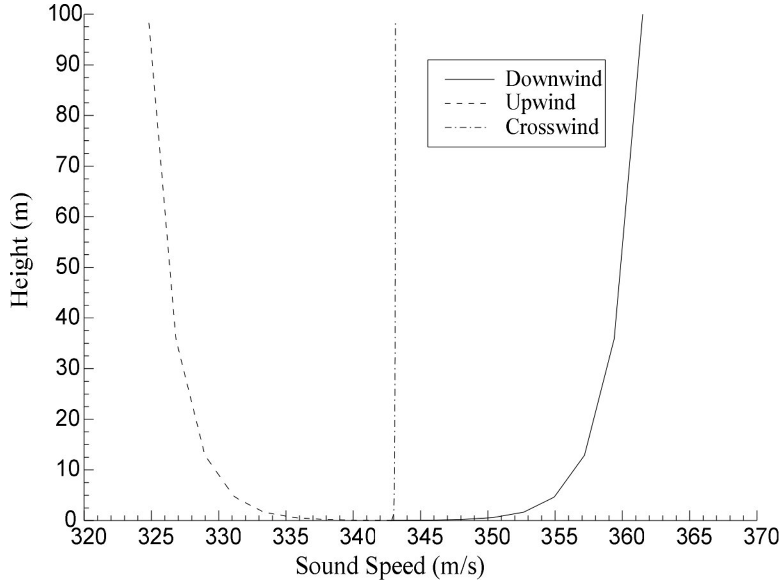

Figure 2: Sound speed profile calculated from similarity profile for a windy spring day.

direction of propagation. In the downwind direction, an acoustic duct is present which indicates long propagation distances. The upwind direction shows decreasing sound speed with height resulting in very poor propagation conditions. The crosswind direction will be dominated by the temperature profile resulting in less intense upward refraction. Using an acoustic propagation model, the effect of this meteorological case can be easily seen, Figure 3. The downwind case has the least attenuation of the acoustic signal. The large variations in the downwind case are due to constructive and destructive interference of direct and reflected waves. If this were an acoustic target, the detection range of a sensor system would vary with azimuth from less than a kilometer to several kilometers.

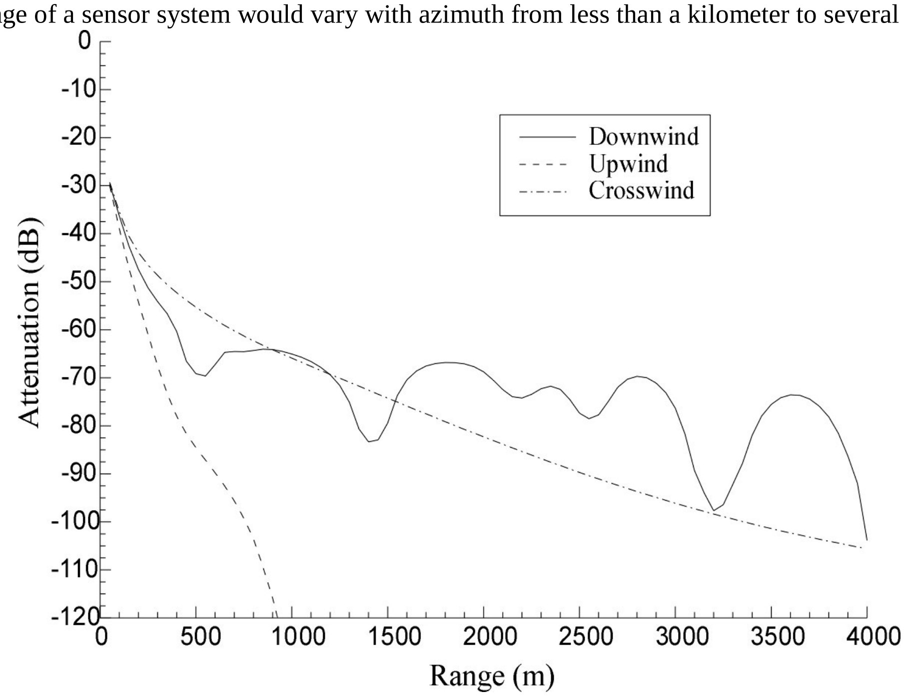

Figure 3: Sound attenuation calculated from sound speed profile for a windy spring day.

5.0 SUMMARY

The temperature and wind speed profiles are important in accurately predicting the mean atmospheric effects on sound propagation. If no temperature or wind speed profiles are available for a specific area or time-of-year, the similarity theory allows an individual to create temperature and wind speed profiles within the surface layer. The problem is determining the similarity parameters to generate these profiles. A model to estimate the similarity parameters was developed by Rachele and Tunick (Rachele & Tunick, 1994). The model uses very basic meteorological data and site information to calculate the similarity parameters. These parameters can be used with a similarity model to generate profiles of the temperature and wind speed within the surface layer. These profiles can be used with a propagation model to calculate the attenuation of sound due to the atmosphere over limited ranges (< 5 km). Even with the limitations on similarity theory, this technique will have many applications when calculating the impact of the atmosphere on acoustic sensor performance when no meteorological profiles are available.

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